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Innovative Strategies and Machines for Physical Weed Control in Organic and Integrated Vegetable Crops

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Weed control is one of the most serious problems in vegetable crops, limiting cultivated plants correct development, yields, product quality and farmers income. Therefore, the aim of this work was to set up and improve innovative strategies and machines for physical (mechanical and thermal) weed control in organic or “integrated” vegetables production in many important areas of Northern, Central and Southern Italy. Therefore, on-farm experiments were carried out since 1999 on fresh marketable spinach, processing and fresh market tomato, cauliflower, savoy cabbage, greenhouse cultivated leaf beet, garlic, chicory, fennel and carrot. These research activities started are still ongoing. The traditional farm weed management system was always compared to one or more innovative strategies that were defined according to the characteristics of the environment (i.e. soil type and conditions, water availability, etc.), typology of cultivation, crop rotation, expected technical and economical results. The innovative strategies were the combination among preventive methods (false or stale seed-bed technique), cultural methods (i.e. crop spatial arrangement that was often adjusted in order to improve operative machines effectiveness) and direct control methods (flaming, precision hoeing, etc.). Different kinds of specific implement such as flex tine and rolling harrows (patented by the University of Pisa, patent n. PI/2004/A/000071), and flamers (designed and realized by the University of Pisa) were used to perform false or stale seed-bed technique. Precision hoes equipped with rigid tools and hoe-conformed rolling harrows, equipped with elastic tines for selective intra-row weed control, were used to perform post emergence interventions. The use of the innovative weed management systems always resulted in significant weed abundance reductions (from 70 to 100 %), relevant yield increases, high contractions of manpower requirement (from 20 to 80 %) and consequent relevant reductions of costs and increases of farmers gross incomes (from 15 to 75 %) in comparison with those obtained performing the standard systems. The results of these on-farm experiments emphasise that physical weed control can be effectively performed using the innovative machines designed and built at the University of Pisa. These machines can also be easily adjusted in order to be used in other crops and agricultural contexts.
Moreover, the present versions of the machines, realized as “low-tech” implement in order to be available on the market at low costs, were recently modified within the RHEA Project, a 7th Framework Programme EU funded research project, in which an automatic and robotized hoeing-flaming machine able to perform VRA cross flaming was designed, fully realized and tested obtaining very promising results.

1. Introduction

The market of organic products has significantly grown in the last decade in Europe (Willer et al., 2013). Italy is one of the most important organic producers in Europe, especially concerning vegetable crops, which involved over 23,000 ha in 2011 (European Union, 2013).

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Weed control in organic agriculture is a major problem, especially in organic vegetable production, where the crop is always characterized by low competitiveness with respect to the wild plant species (Barberi, 2002). However, the use of herbicides is forbidden and other alternatives have to be adopted by the farmers.
I.e., one of the main technical constraints to organic carrot growing is the limited range of effective direct weed control means capable of replacing chemical herbicides. Many researches have focused attention on preventive, cultural and direct post-emergence physical control strategies in order to provide the carrot crop with a competitive advantage during the entire cycle (Bàrberi, 2002). At present, the main limitation of direct mechanical means is the intra-row weed control. As a matter of fact, an effective post-emergence intra-row weed control could reduce considerably the relevant time required for hand weeding, a practice that is indispensable in carrot production.
Physical weed control is the most common alternative adopted by organic farmers and includes mechanical means used for soil tillage (Cloutier et al., 2007) and the use of thermal radiation for weed control (Ascard et al., 2007). The use of mechanical means before crop establishment is called false seedbed technique. It consists of stimulating weed seed germination and subsequent weed suppression by tillage. This allows to obtain a relevant reduction of weed seed-bank (Cloutier et al., 2007). The false seedbed technique can be carried out by means of various machines: chain, flex-tine, rolling harrows, etc. (Cloutier et al., 2007).
On the other hand, thermal weed control can be always used before crop planting, emergence or transplanting together with mechanical methods for weed seed-bank depletion (in this case this technique is called stale-seedbed). Thermal means can be also applied directly to the crop after its establishment in heat tolerant, species (i.e. garlic, maize and onion) (Ascard et al., 2007).
Moreover, the application of precision agriculture technologies and sensors increased in the last years also for physical weed control, according to the development of high tech machines which are able to detect and discriminate crops and weeds and eliminate the weeds in the intra-row space. Many solutions are now available on the market and consist in the use of discs or blades which move in and out from the crop row (Ascard et al, 2014).
Another interesting application of precision agriculture is the combination between inter-row mechanical cultivation and in-row flaming in tolerant crop. Sensors and actuation systems provide the right distance from the crop row to the flame. Moreover, the flame can turn off and on and changes automatically the degree of heat transmission, according to weed presence (Frasconi, 2014).
A short review on the results obtained on physical weed control in three representatives vegetable crops in Italy, by the Department of Agriculture Food and Environment and the Experimental Farm “Enrico Avanzi” of the University of Pisa, is reported in this paper.
The three vegetables are carrot, garlic and fennel, which are typical Italian products.

2. The trials

Different trials were carried out in three different places in Italy using different specialty organic vegetable crops, carrot, fennel and garlic. In the three contexts a traditional farming system was compared to an innovative farming system which included advanced methods for non-chemical weed control.
Carrot was sown and grown in Sicily, in the Provence of Catania (Southern Italy). The experimental trials were carried out in the 2005-2006 growing season. The traditional organic farming system consisted in a two band special arrangement of the crop, where only hand weeding/hoeing could be performed, while the innovative farming system consisted in a 5 rows space arrangement and the use of the stale seedbed technique (rolling harrow and flaming) and post emergence precision hoeing (operative machine mounted on the tractor) and manual weeding (Peruzzi et al., 2008a). Manual weeding was always needed because carrot is a low competitive crop and characterized by a long growth cycle. Within the innovative farming system, hand weeding could be applied before or after precision hoeing.
Fennel was transplanted and grown in the Fucino Valley (Avezzano, Provence of L’Aquila, Central-Southern Italy) in 2004-2005 and the traditional organic farming system consisted in conventional cultivation and hand weeding/hoeing. The innovative organic farming system consisted in stale-seedbed technique and post-transplanting precision hoeing treatments with innovative machines (Peruzzi et, al. 2007).
Garlic was planted (bulbs) and grown in Vessalico (Provence of Imperia, Central-Northern Italy) in 2006-2007, where garlic is a typical niche high-quality product. The traditional organic farming system consisted in manual weeding while the innovative strategy provided a stale-seedbed technique and post-emergence precision hoeing and flaming, as garlic is an heat tolerant plant (Peruzzi at al., 2008b).

3. The Machines

The rolling harrow can be used in both the false/stale seedbed technique before sowing and in early precision hoeing after crop emergence/transplanting (Figure 1). The machine has a square frame bearing two axles and a three-point linkage (Peruzzi et al., 2007). Spike disks are placed on the front axle and cage rolls on the rear axle. The front and rear axles are connected by an overdrive ($\tau = 2$). Discs and rolls of different sizes can be interchanged with a very simple blocking system. The rolling harrow eliminates the weeds via spiked discs that till the soil at a depth of 3-4 cm, followed by the cage rolls that work at a high peripheral speed and till the soil at a depth of 1-2 cm as well as eliminating any trapped inside small clods that otherwise could survive especially in wet or crusty soils (Peruzzi et al., 2008a). The discs and rolls are placed close together when the rolling harrow is used to prepare the seedbed and for non-selective mechanical weed control in the false/stale seedbed technique, while they are spaced apart for inter-row weeding. Intra-row weed control is performed by couples of flexible tines (working as both vibrating teeth and/or torsion weeders) arranged on a static axle positioned behind the discs and rolls axles. The rolling harrow has a steering handle system for precision weeding (used in fennel). The width of the machine was changed depending on the crop, it was 1,4 m for carrot and garlic and 2 m for fennel (Peruzzi et al., 2008b). The used working speeds were always quite high, ranging from 6 up to 9 km h^{-1}.

Figure 1: Rolling harrow at work before crop planting

The flaming machines control weeds by the use of an open flame. In these experiments they were equipped with 25 or 50 cm wide rod burners, for a total working width ranging from 1.5 m (in carrot and garlic) and 2 m (in fennel) (Figure 2). This treatment has the advantage of eliminating weeds without stimulating new emergence, because the soil remains undisturbed. The machine is equipped with common 15 kg LPG tanks placed into an on purpose made hopper (Peruzzi et al., 2007). Furthermore, these machines are also equipped with an innovative heat exchange system, in order to avoid thanks cooling during the flaming treatment (due to the LPG passage from liquid into gaseous phase). It consists in heating the water contained into the hopper utilizing the emissions coming from the tractor exhaust head.

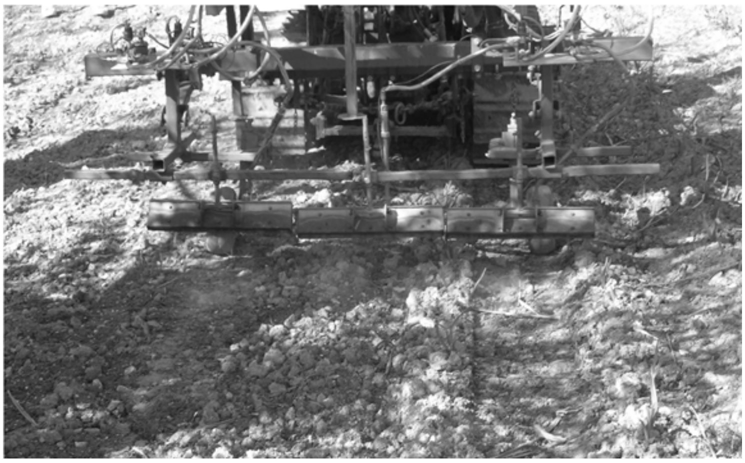

Figure 2: Flaming machine during a post-emergence treatment in garlic

A security system, characterized by one electromagnetic valve per couple of burners or single burner, stops the LPG flow in case of flame switch off. A minimum-maximum valve allows to reduce LPG working pressure (just leaving a pilot light) during tractor turning and transfer, in order to reduce LPG consumption and fire risk. The treatment was performed only in pre-emergence and pre-transplanting phase in carrot and fennel, while it was used after crop emergence in garlic as it is a heat tolerant specie (Peruzzi et al., 2008a). Working speeds ranged from 3 up to 7 km h^{-1} and LPG pressures ranged from 0.2 and 0.4 MPa, allowing to maintain in any case a LPG biological dose of about 35 kg ha^{-1} (Peruzzi et al., 2008b).

The precision hoeing machine is characterized by a 2 m wide frame and was equipped with 6 rigid elements for inter-row cultivation (a central "foot-goose" tool and two side "L" shaped sweeps or discs) and elastic elements for intra-row selective weed control (torsion weeders and vibrating tines) and a guidance system consisting in a seat, steering handles and directional wheels (Figure 3). The vibrating tines, which work in vertical position, have their longer segment bent at several points in order to till very close to the crop row (Peruzzi et al., 2007). The torsion weeders, on the other hand, work in horizontal position; a torsion spring enables the tines to flex when they meet a fairly developed plant (generally a crop plant but it could also be a large weed) that opposes resistance to the implement action (Peruzzi et al., 2008a). The position of both tools can be modified according to the treatment aggressiveness required. Treatment becomes more intense when the tines are positioned close to the row crop. The inter-row distance was set to 0.45 m for fennel and 0.20 m for carrot and garlic. Average working speed was about 2 km h^{-1} and working depth was about 4 cm (Peruzzi et al., 2008b).

Figure 3: Precision hoe at work in fennel

4. Experimental assessments

All the main operational characteristics concerning the mechanical-thermal and mechanical-thermal-straw strategies were recorded. These included working depth, operating speed, working productivity, operating time, fuel and LPG consumption.

Weed infestation was characterized by weed density and dry weed biomass. Weeds were counted within a rectangular frame of 0.25 m × 0.30 m. Weed dry biomass was sampled within a frame of 1 m^2 in three randomly selected sampling points in each plot. The same procedure was used to sample crop yield.

Weed dry biomass and marketable crop yield were subjected to a combined ANOVA and Fisher's Protected LSD test was used with $\alpha=0.05$ for means separation.

5. Results

Concerning yield, a significant increase was assessed in garlic and fennel within the innovative organic farming system while significant differences were not observed between the two compared strategies in carrot, despite the more incisive treatment. This is probably due to the longer growth cycle, the different growing season, the different climate conditions and the different weed seedbank of the carrot in Sicily. The increase was 3 % for carrot (not significant), 38 % for garlic and 20 % for fennel (Table 1).

Table 1: Yields of the three crops within two different cropping systems (Mg ha^{-1}). Different letters on the same column mean significant difference for the LSD test at $P<0.05$ (reprocessed from Peruzzi et al. 2007, 2008a and 2008b).

	Carrot	Garlic	Fennel
Traditional organic	33.0 ns	2.1 b	30.7 b
Innovative organic	33.9 ns	2.9 a	36.9 a

The yield increase was probably due to a better weed control, as shown in table 2. As a matter of fact, weed dry biomass at harvest was always significantly lower in the innovative farming systems (-76 % for carrot, -66 % for garlic and -40 % for fennel). These results were obtained according to the use of the innovative machines for physical weed control in combination with hand weeding. The traditional farming system consisted only of hand weeding/hoeing in garlic and carrot, while in fennel it was combined with ordinary inter-row cultivation. In the innovative weed control strategy used in garlic, hand weeding was not necessary.

Table 2: Weed dry biomass at harvest (g m^{-2}). Different letters on the same column mean significant difference for the LSD test at $P<0.05$ (reprocessed from Peruzzi et al. 2007, 2008a and 2008b)

	Carrot	Garlic	Fennel
Traditional organic	17.2 a	511.1 a	26.3 a
Innovative organic	4.1 b	188.4 b	15.6 b

The application of the innovative strategies resulted also in relevant reductions of the hand labour time needed for weed control (that often represents the main cost for organic vegetable producers) in comparison with the use of the traditional managements. A relevant decrease in labour demand for weed control was observed in all the three crops. In carrot the stale seedbed technique and the precision hoeing plus hand weeding required less then half the time required for the traditional hand weeding without any mechanization. A greater reduction was observed in garlic, where the innovative system did not need hand weeding. Labour time was also reduced by 30 % in fennel.

Table 3: Labour time for weed control for the three crops within two different cropping systems (h ha^{-1}) (reprocessed from Peruzzi et al. 2007, 2008a and 2008b)

	Carrot	Garlic	Fennel
Traditional organic	844.0	300.0	188.2
Innovative organic	278.5	50.0	130.1

6. Conclusions

Innovative strategies for non-chemical (physical) weed control in organic horticulture were tested in different contexts in Italy: carrot in Southern Italy, fennel in Central-Southern Italy and Garlic in Northern-Central Italy.

The aim was to improve crop yields and reduce the labour demand for hand weeding, which often is the major cost for organic vegetables growers.
The goal was achieved according to a relevant yield increase in fennel and garlic (about 20 and 40 %) while not significant differences were observed in carrot. Weed control significantly improved in all the experimental areas, as the proper use of the innovative machines always provides a weed dry biomass reduction at harvest (ranging from 40 up to 80 %). Another important result concerns the reduction of labour time for hand weeding/ hoeing. On this regard, relevant reductions (ranging from 30 up to 80 %) were observed in all the tested crops.
According to these results, it is possible to state that the innovative machines for physical weed control can represent an important mean for organic vegetable growers in order to reduce costs and increase their income. Moreover, the innovative machines are low-tech equipment, which can be easily adjusted or modified depending on the different agronomic context and purchased according to their availability on the market at low cost.

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